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Discussion

How much anthropogenic carbon fixation do we need?

Wensheng Xiao [a], Simeon J. Smaill [b], Xiaoqi Zhou [a,*]

[a] Zhejiang Tiantong Forest Ecosystem National Observation and Research Station, Shanghai Key Lab for Urban Ecological Processes and Eco-restoration, School of Ecological and Environmental Sciences, East China Normal University, Shanghai 200241, China
[b] Scion, PO Box 29237, Riccarton, Christchurch 8440, New Zealand

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ABSTRACT

Carbon dioxide (CO_2) emissions resulting from human activities are the primary driver of global warming. The reduction of emissions is the key solution to limit global warming, although it is likely that some level of anthropogenic CO_2 emissions will remain unavoidable. Therefore, it is crucial to determine the amount of carbon fixation necessary to achieve net zero CO_2 emissions and the extent of anthropogenic carbon fixation required to meet this target. According to the RCP2.6 scenario, which aligns with the criteria outlined in the Paris Agreement to keep global warming below 1.5 °C, we have calculated that anthropogenic activity must achieve 1.5 gigatons (Gt) of CO_2 to reach net zero CO_2 emissions by 2050. This figure will significantly increase if emissions are not reduced by 2050. However, estimating the additional anthropogenic fixation required becomes challenging due to potential disruptions to natural fixation. Therefore, we strongly recommend conducting further research on the stability of natural carbon fixation processes to establish meaningful goals for anthropogenic carbon fixation.

In recent decades, global warming has had a significant impact on terrestrial ecosystems, leading to increased frequency of extreme droughts, high-temperature events, forest fires, and reductions in food production (IPCC, 2021). The rise in temperature can also affect the efficiency of trophic transfers, potentially reducing biomass at higher trophic levels as more carbon is lost to respiration (Thakur, 2020). Climate change scenarios suggest that a 2 °C increase in terrestrial ecosystems across various regions of the world could lead to ecosystem collapse (IPCC, 2021; Guiot and Cramer, 2016). These outcomes are already having negative effects on human well-being, and model predictions indicate that if current trends continue, the impacts will intensify (IPCC, 2021). Moreover, global warming could promote the spread of epidemics and the release of ancient viruses, further threatening human health (Carlson et al., 2022). Therefore, limiting global warming has become a challenge of utmost importance.

Global warming is primarily driven by the increased concentrations of greenhouse gases in the atmosphere, which are a result of significantly higher emission rates in the past two centuries (IPCC, 2021). Among these gases, carbon dioxide (CO_2) is the most significant contributor, accounting for over 70 % of the global greenhouse effect (Friedlingstein et al., 2022). While other greenhouse gases like methane, nitrous oxide, and fluoride compounds have a lesser impact on the overall greenhouse effect, their radiative forcing potential is much higher than that of CO_2. Therefore, even small changes in their atmospheric concentrations can have a disproportionately larger effect on global warming (IPCC, 2021). Consequently, concerns regarding the emissions of these trace gases have also grown in recent decades (IPCC, 2021; Guiot and Cramer, 2016). However, reducing CO_2 emissions is still considered the primary target for achieving meaningful reductions in global warming.

The concentration of atmospheric CO_2 is determined by the balance between carbon emissions (carbon sources) and carbon fixation (carbon sinks). Various natural processes release CO_2 into the atmosphere, such as respiration and volcanic eruptions. Anthropogenic sources, on the other hand, are primarily linked to the use of fossil fuels, with construction and land use changes also identified as significant sources (IPCC, 2021; Friedlingstein et al., 2022). While natural CO_2 emissions are much larger in scale than anthropogenic sources, the additional anthropogenic CO_2 exceeds the global capacity for removing CO_2 from the atmosphere through natural fixation processes (IPCC, 2021). Between 2010 and 2019, approximately 54 % of anthropogenic CO_2 emissions were absorbed by natural processes (31 % in terrestrial ecosystems and 23 % in oceans), while the remaining 46 % remained in the atmosphere (IPCC, 2021). Since the industrial revolution, the average annual anthropogenic CO_2 emissions worldwide have been around 38 gigatons (Gt), with 34.8 Gt coming from fossil fuel combustion and 3.2

* Corresponding author.
E-mail address: xqzhou@des.ecnu.edu.cn (X. Zhou).

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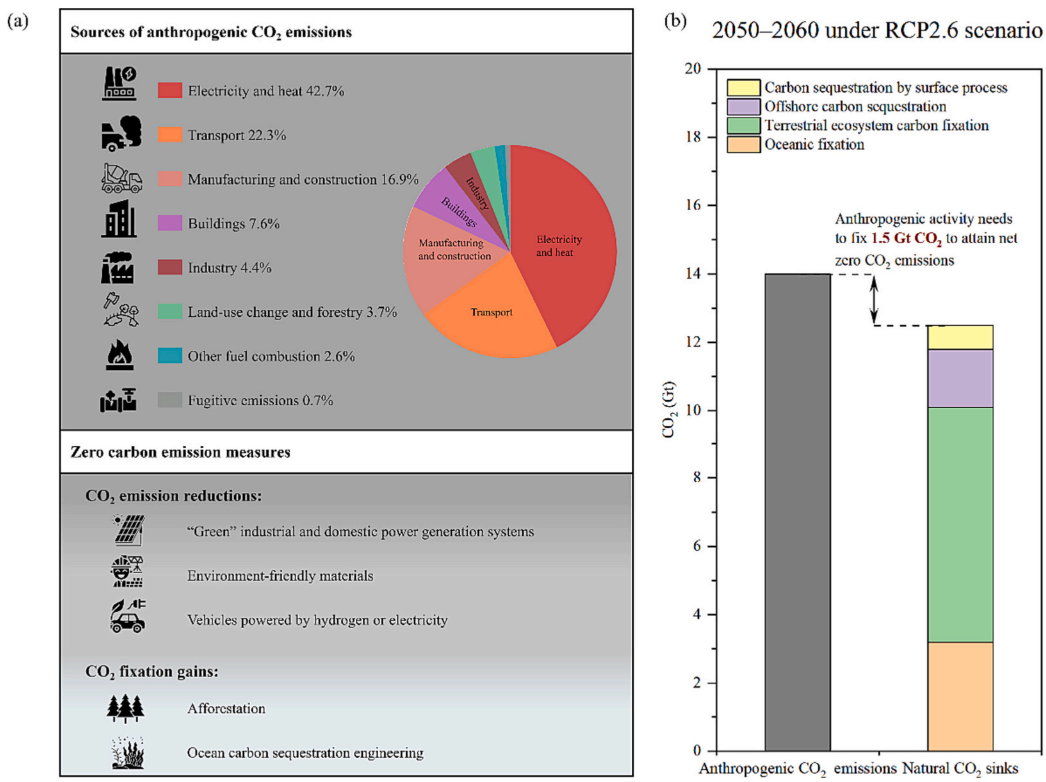

Fig. 1. In 2019, the sources of anthropogenic CO_2 emissions and effective measures to achieve zero carbon emissions goals are as follows: (a) In the RCP2.6 scenario, which assumes strong global emission reduction measures, greenhouse gas emissions are projected to peak in the mid-21st century and gradually decrease, resulting in a reduction of approximately 70 % by 2100. This scenario aims to limit the global average temperature increase to within 2 °C above pre-industrial levels, in line with the goals of the Paris Agreement. Between 2050 and 2060, the estimated anthropogenic CO_2 emissions and natural CO_2 sinks have a difference of 1.5 Gt CO_2. To achieve net zero CO_2 emissions, these additional CO_2 emissions need to be offset through anthropogenic activities (b).

Gt caused by land use changes. Out of the 38 Gt of CO_2 emitted, 17.5 Gt (46 %) are added to the atmosphere, resulting in an annual increase of about 2 ppm in atmospheric CO_2 concentration (Friedlingstein et al., 2022). Achieving a global carbon-neutral scenario does not mean completely eliminating all CO_2 emissions, as certain essential aspects of industrial and agricultural activities are likely to always act as carbon sources. Instead, it involves effectively offsetting all emissions through increased natural fixation and anthropogenic fixation technology (Cuéllar-Franca and Azapagic, 2015).

In 2019, global anthropogenic CO_2 emissions reached approximately 36.7 Gt CO_2. The distribution of these emissions, as shown in Fig. 1, highlights the need for multiple mitigation strategies to achieve global carbon neutrality. One example that has been extensively discussed in various forums is the large-scale implementation of "green" power generation systems in both industrial and domestic settings. These systems, such as wind, solar, hydro, nuclear, and geothermal, can replace CO_2-emitting fossil fuel systems (Chu et al., 2017). To reduce emissions from construction, integrating more wood and wood fiber products into concrete buildings is a viable solution (Fennell et al., 2022). This is particularly important considering the significant energy footprint associated with cement production. In terms of transportation, switching to vehicles powered by hydrogen or electricity can help reduce emissions (Gray et al., 2021). However, it is important to note that these pathways, along with others, will not completely eliminate carbon emissions. Achieving carbon neutrality requires incorporating strategies to enhance carbon fixation.

In recent decades, the oceanic fixation of anthropogenic CO_2 has remained relatively stable, accounting for 23 % of emissions, which is currently equivalent to around 8.4 Gt CO_2 per year (IPCC, 2021). While it is challenging to predict significant changes to this ratio in the future, we assume that this level will be maintained. According to the RCP2.6 scenario, which aligns with the criteria outlined in the Paris Agreement to limit global warming below 1.5 °C, the terrestrial ecosystem's carbon sequestration capacity from 2050 to 2060 is projected to be approximately 6.2 Gt CO_2 per year (Shi et al., 2021). If the ecosystem is managed to support carbon fixation, an additional 0.7 Gt CO_2 per year can be added to the carbon sinks, resulting in a total of approximately 6.9 Gt CO_2 per year (Fuss et al., 2018; Lu et al., 2022). Moreover, offshore wetlands and marine sediments hold significant potential for carbon fixation, with an estimated capacity of nearly 1.7 Gt CO_2 per year (Regnier et al., 2022). Other pathways for carbon fixation include surface processes such as the incorporation of organic carbon in the precipitation of limestone and the deposition of soil carbon in rivers, lakes, and coastal environments through erosion. Currently, the extent of these effects is not precisely known but is estimated to be around 0.7 Gt CO_2 (Regnier et al., 2022).

These values provide a framework for estimating the amount of anthropogenic carbon fixation required to achieve global net zero CO_2 emissions under the RCP2.6 scenario (IPCC, 2021). According to this framework, in the time period of 2050–2060, global annual anthropogenic CO_2 emissions are projected to be approximately 14 Gt. Of this, 3.2 Gt of CO_2 will be fixed by the ocean, maintaining the 23 % rate. Terrestrial ecosystem carbon fixation is estimated to be 6.9 Gt CO_2, while offshore carbon sequestration and carbon sequestration by surface processes are projected to account for 1.7 Gt CO_2 and 0.7 Gt CO_2 respectively. In total, these measures will result in the fixation of 12.5 Gt CO_2, leaving a remaining requirement of 1.5 Gt CO_2 to achieve net zero CO_2 emissions through anthropogenic activity. If carbon emissions exceed those projected under the RCP2.6 scenario the impact on the required anthropogenic fixation increases proportionally. For example, if anthropogenic emissions are 22 Gt CO_2, oceanic fixation is proportionally increased to 5.1 Gt CO_2 and the amount of CO_2 that needs to be fixed through anthropogenic activity increases by 6.1 Gt to 7.6 Gt. Furthermore, it is important to consider the potential impacts of these increased CO_2 emissions on terrestrial carbon fixation. It is possible that these impacts could reduce the capacity for terrestrial ecosystems to fix carbon, further increasing the amount of anthropogenic CO_2 fixation required to achieve net zero emissions. It is worth noting that there is uncertainty surrounding these estimates. By 2050, global climate change or other ecosystem-level disturbances are likely to affect the carbon fixation capacity of terrestrial, marine, and oceanic ecosystems, even if CO_2 emissions are reduced to 14 Gt. Despite this uncertainty, these estimates currently represent the best available information. In the meantime, we strongly recommend further research to better understand the stability of carbon fixation processes in these environments (Ciais et al., 2021).

To achieve a net zero carbon world, it is crucial to focus on capturing CO_2 through anthropogenic processes. The success of this endeavor relies on the development of underlying technologies and the implementation of effective economic and policy measures. Given the current progress towards this goal, it is likely that governments will need to provide subsidies for industrial carbon sequestration. This financial support will be essential in achieving the target of capturing 1.5 Gt CO_2 annually (Fuss et al., 2018). However, considering the magnitude of CO_2 emission reductions required for RCP2.6 and the lack of progress in achieving these reductions (Fuss et al., 2018; Friedlingstein et al., 2022), it is prudent to aim for anthropogenic fixation of at least 4.5 Gt CO_2. This approach would not only allow for potential reductions in fixation by other processes but also provide a more substantial buffer to meet the necessary reductions.

Given the unprecedented magnitude of the global effort needed to address this issue, we propose that all countries enhance cooperation in the realm of climate change by establishing climate change working groups. These groups would be responsible for developing and enforcing timelines for reducing CO_2 emissions and increasing CO_2 fixation gains. Additionally, it is essential to regularly monitor the carbon fixation capacity of terrestrial, oceanic, and marine environments to enable meaningful adjustments to anthropogenic carbon fixation targets. Without such dedicated actions, we will fall short of achieving the objective of carbon neutrality by the mid-century.

CRediT authorship contribution statement

Xiaoqi Zhou, Wensheng Xiao conceived the idea for the paper and led the analysis and writing. Simeon J. Smaill contributed to the analysis and development of the argument. All authors contributed to drafting, reviewing and editing the paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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